Power System Design Concepts of a Reusable Launch Vehicle-Technology Demonstrator (RLV-TD)

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***Abstract*— Expendable Launch Vehicles are designed with a single mission perspective. Reusable Launch Vehicle design aims for reusability and maintainability for multiple missions. Power system of such missions has features that are distinctive from operational launch vehicles like PSLV & GSLV. The instrumentation, Navigation Guidance & Control, pyro and actuation system power are derived from Li ion batteries, which is a notable feature of Reusable Launch Vehicle- Technology Demonstrator. RLV-TD power system consists of a unified redundant power bus running throughout the vehicle unlike conventional launch vehicles. This paper discusses the configuration of electrical power distribution system of RLV-TD highlighting the constraints and design considerations. Load requirements and power characteristics are defined. Techniques adopted for fault protection and redundancy to achieve reliability are discussed. Battery capacity estimation method followed for continuous and pulse current requirements are described.**

Keywords— Lithium Ion Batteries; Reusable Launch Vehicle

Nomenclature:

RLV-TD	:	Reusable Launch Vehicle Technology Demonstrator
HEX	:	Hypersonic Experiment
TDV	:	Technology Demonstrator Vehicle
NGC	:	Navigation Guidance & Control
BLDC	:	Brushless DC Motor
BSCE	:	Base Shroud Control Electronics
SITVC	:	Secondary Injection Thrust Vector Control
RCS	:	Reaction Control System
CTR	:	Checkout Terminal Room

I. Introduction

The objectives of Reusable Launch Vehicle Technology Demonstrator Hypersonic Experiment (RLV-TD-HEX01) mission is to evaluate the hypersonic aero thermodynamic characteristics, thermal protection systems, hypersonic re-entry mission management including un-powered glide and landing at pre-specified location and reliability of autonomous NGC systems. RLV-TD presents several challenges for the design of power distribution system. Few of the most significant are:

- Orientation constraints: The flight trajectory involves ascent and descent. Conventional aerospace batteries such as Silver -Zinc (Ag Zn) batteries experience the problem of electrolyte leakage issues with changing orientation.
- Space constraints: Stringent space and weight limitation due to small and compact structure of the vehicle.
- Environmental factors: The vehicle has to experience extreme temperature and pressure conditions.
- Reusability: Reusability implies the battery has to undergo multiple charge-discharge cycles.
- Winged body: The aerodynamic control is achieved through control surfaces (fins during ascent and elevons and rudders during descent). These control surfaces are operated by a hydraulic power plant driven by brushless DC (BLDC) motor which requires a high power source (100V/120A).

Many new system engineering design concepts are absorbed in RLV-TD and this paper brings out certain design considerations and methodologies for the power system design in solving these unique problems. Selection of Lithium ion batteries over Silver Zinc batteries is done considering its better wet life, reusability, high pulse performance and no constraints with respect to orientation [1, 2]. A common redundant power bus concept is adopted here instead of placing separate set of batteries in different sub-assemblies. Battery count is reduced by selectively combining electrical systems. This scheme provides considerable reduction in battery count and electrical umbilical lines. BLDC motor high power requirement (100V/120A) is catered using a 50AH Li-ion battery. Lithium ion battery electrical power characteristics in relation to load system requirements and distribution system design are described.

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II. SALIENT FEATURES OF RLV-TD POWER SYSTEM

A. Power Sources

RLV-TD consists of two stages- Technology Demonstrator Vehicle (TDV) and Base Shroud (BS). Lithium ion batteries [1] are used for the following:

- Avionic system: Avionic system power is derived from 3nos. of Avionic Batteries (Lithium ion batteries; 32V/16AH). This includes Instrumentation system, Navigation, Guidance & Control (NGC) System and RF Systems.

- Pyro System: Li-ion batteries similar to that of Avionic Batteries are used for firing the squibs of the sequencing pyro events. In addition to that it supplies power SITVC actuators and RCS thrusters.

- Actuation System: 105V/50AH Lithium ion battery serves the 10kW(100V/120A) power requirement of the BLDC motor. ON/OFF control of 100V power is achieved using high voltage contactors.

B. Power Distribution & Control

Dual redundant 28V power bus derived from Avionic Battery is distributed throughout the vehicle for avionic system powering. Lower stage power is routed through power cut-off relays. All major Avionic packages have built in DC-DC converters and the output is routed within the respective stacks only. External to internal battery changeover is achieved through a Power-Switching Module (PSM). PSM has provisions for individual ON/OFF, power cut-off, Relay Pole Voltage monitoring, Battery Voltage Monitoring and battery charging and monitoring [6]. Power interruption during INT/EXT switchover is avoided by routing the external supply directly to the pole of the switching relay through a diode. Surge suppression diodes are provided across relay coils.

C. Reliability considerations and redundancy

Power sources are made independent and redundant wherever system redundancy exists. In case of battery ORing, battery capacity is computed for single battery operation to ensure functionality in case of one battery failure [3, 5]. When redundant elements are operated from ORed power sources, current limiting is provided in each element. The monitoring of power system health parameters is cross-strapped. Two independent chains of instrumentation are powered from two independent batteries. Sensors/signal conditioners to transmitter of a chain are made independent of the other. Related information is monitored through both chains so that failures in one chain do not affect the availability of critical information. Dual redundant chains for Navigation sensors are powered from two independent power modules, which in turn derive their input from two independent batteries. Wherever triple modular redundancy (TMR) exists three sets of batteries are used. Line redundancy and connecter redundancy is ensured for power lines and pyro command lines. Power interruption to processors/FPGA based packages due to relay chattering is avoided by using solid-state relay in parallel with electromechanical relays.

III. CHANGES FROM OPERATIONAL LAUNCH VEHICLES

Conventionally, independent Batteries are used for individual systems. In RLV-TD, batteries are combined for

- Instrumentation and Navigation, Guidance & Control systems
- Tele-command and destruct systems
- SITVC actuators, RCS thrusters & Pyro system.

Thus, battery count is reduced from 18 numbers as per conventional approach to 8 numbers (Table-1).

TABLE I. BATTERY DISTRIBUTION IN RLV-TD

Function	Conventional Approach			RLV-TD		
	TDV	***IS***	***BS***	***TDV***	***IS***	***BS***
Instrumentation	2		2	3		
NGC	3					
BS CE			1			
Tele-command	--	2			2	
Destruct	--	2				
Pyro	2		2	2		
SITVC			1			
BLDC	1			1		
Total	8	4	6	6	2	
Total batteries	18			8		

This provides considerable reduction in the number of umbilical lines needed for charging and monitoring. It also reduces the space and mass contribution from the batteries.

IV. LOAD ANALYSIS

A. Continous current

Battery has to cater to the power requirements for a mission duration of 1000s and launch countdown operations. Capacity study is done considering the load requirements during flight, pre-launch operation, internal and launch hold time with sufficient margins. Avionic battery capacity is 16AH, max current requirement is 15A for a duration of 30 minutes (including battery internal duration, launch hold time and mission duration) then the margin available can be computed using the formula

$$\text{Battery Margin(in \%)} = 100 * \left(1 - \frac{\text{I} * \text{T(in minutes)}}{\text{Capacity(in AH)} * 60}\right)$$

Where, I is the continuous current (in Amperes) and T is the duration (in minutes). For Avionic Battery 53.2% margin is available.

BLDC motor current profile is as shown in Figure 1. It consumes 30A before lift-off, 120A for about 100s after lift-off and then 50A upto the end of the mission. For such cases where current is varying, the following equation is made use in capacity estimation.

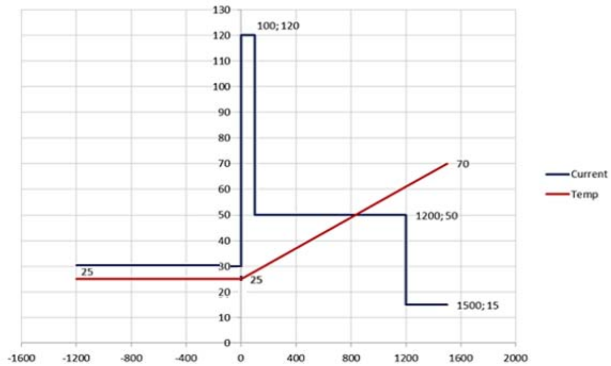

Fig. 1. Temperature & Current profile of BLDC Motor

$$\text{Battery Margin(in \%)} = 100\left(1 - \frac{(\text{i1} * \text{t1} + \text{i2} * \text{t2} + \cdots \text{in} * \text{tn})}{\text{Capacity(in AH)} * 60}\right)$$

Where, i1 is the current (in Amperes) for the duration t1 (in minutes) and so on. For 50AH BLDC battery the estimated margin is 44%.

B. *Pulse current*

Pulse current estimation is done assuming single battery failure so as to analyze the capability of single battery to deliver the peak pulse requirement. The following elements are to be considered- Internal Impedance of the battery, load resistance and battery ORing diodes. The voltage available from the battery is given by,

$$\text{V} = \text{Vbatt} - \text{I(load)} * \text{ro} \qquad \text{---} \qquad (1)$$

Where V is the voltage available for the load, Vbatt is the voltage when no current is drawn from the battery, I (load) is the current drawn and r is the internal impedance. If R0 is the load resistance and Vd is the diode drop, then

$$\text{V} - \text{Vd} = \text{I(load)} * \text{Ro} \qquad \text{---} \qquad (2)$$

Battery characteristics and load characteristics can be generated from equation 1&2. Equating (1) & (2), we get

$$\text{I(load)} = \frac{\text{Vbatt} - \text{Vd}}{\text{Ro} + \text{ro}}$$

$$\text{V} = \text{Vd} + \frac{\text{Vbatt} - \text{Vd}}{\text{Ro} + \text{ro}} * \text{Ro}$$

Battery Characteristics is a function of internal impedance of the battery which however, is not constant in the case of lithium ion batteries. In order to obtain the internal impedance of the battery, pulse discharge was carried out for varying current and is listed in Table 2.

TABLE II. VOLTAGE VERSUS PULSED CURRENT FOR LITHIUM ION BATTERY

Voltage (V)	Current (A)	Computed Internal Impedance (Ohms)
26.58	80	0.06775
27.35	70	0.066429
27.9	60	0.068333
28.56	50	0.0688
29	40	0.075
29.77	30	0.074333
30.32	20	0.084
31.01	10	0.099

A load characteristic is plotted for various values of load current. For a pyro function, the squib resistance, current limiting resistances, line resistance etc needs to be accounted. If multiple squibs are getting fired simultaneously individual currents are to be added up. The net load resistance for simultaneously firing squib functions can be found by,

$$\frac{1}{\text{Ro}} = \left[\frac{1}{\text{l1} + \text{r1} + \text{sq1}} + \frac{1}{\text{l2} + \text{r2} + \text{sq2}} + \cdots . \frac{1}{\text{ln} + \text{rn} + \text{sqn}}\right]$$

Where ln is the line resistance, rn is the current limiting resistor, and sqn is the squib resistance of the nth squib. The current limiting resistance is decided such that the squib current does not exceed/fall below the recommended squib current (4-8A for PSQ7, 5-10A for ZPP squibs). In RLV-TD peak pulse requirement is during HS9 separation when 12 separation squibs get fired simultaneously [7]. The case is plotted in Figure 2. The point of intersection gives the operating point (26.6V, 78A). It can be seen that 78A is the peak pulse current drawn from the battery and the voltage at the peak current is 26.6V [8].

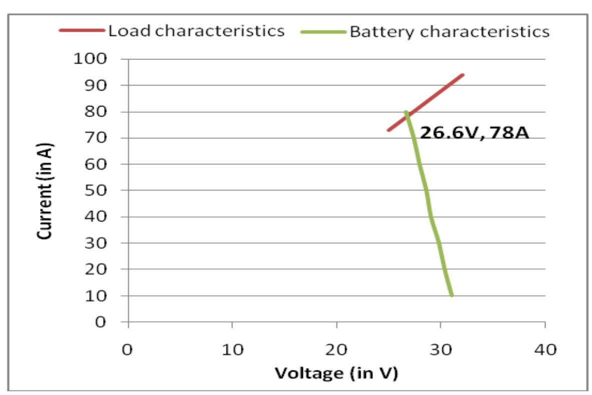

Fig. 2. Pulse Current Estimation for a single battery

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In nominal case, only half the load is expected on either of the batteries as two batteries are ORed. Each battery will be catering to the requirement of 6 squibs. A pulsed current of 42A is expected from both batteries and the voltage at the instant is 29V as given in Figure 3.

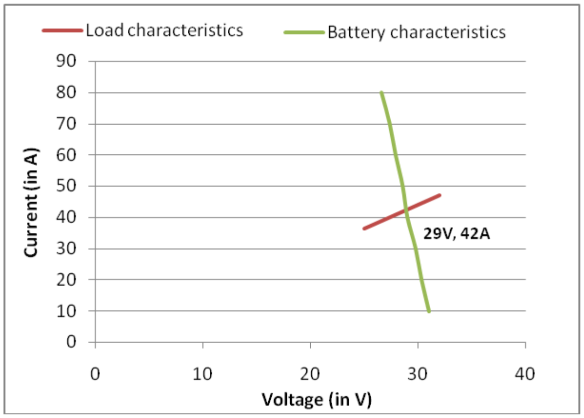

Fig. 3. Pulse Current Estimation for two batteries

RLV-TD HEX-01 flight data shows that 39.5A and 39.8A are the currents drawn from Pyro battery 1 & 2 respectively at the time of HS9 separation and 30.1V and 30.3V are the battery voltages at that instant (Figure 4 & 5) and the values are close to the prediction.

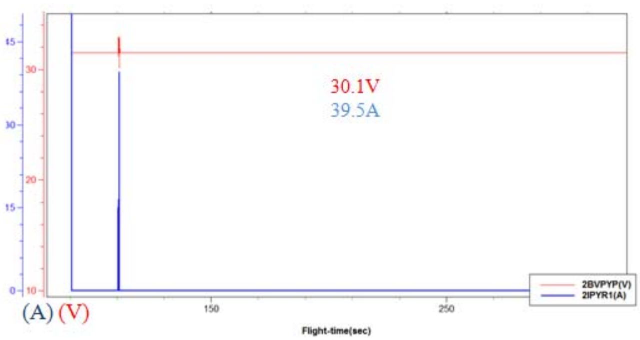

Fig. 4. Pyro Battery-1 voltage and current during flight

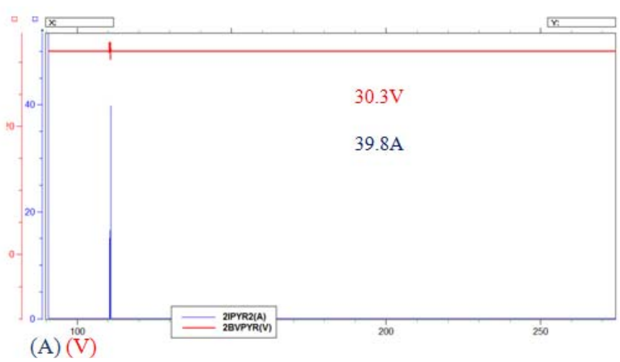

Fig. 5. Pyro Battery-2 voltage and current during flight

V. External Power Supply

During different phases of testing of onboard Avionics systems, External Regulated power supplies are used in place of Battery. Checkout systems have software interlocks for over-current and over-voltage protection. The power supplies are kept in the Checkout Terminal Room (CTR) for most of the systems. The approximate cable length from CTR to launch pad junction box is 200m. External power supplies for all the systems are routed through Electrical Umbilical. Relay pole Voltages are monitored through On-Board Checkout Computer and is given by,

$$\mathrm{RPV} = \mathrm{Vset} - \mathrm{I} * \mathrm{Rpath} - \mathrm{Vd}$$

Where Vset is the voltage set at CTR, Rpath is the line resistance and Vd is the diode drop. RLV-TD has 3 chains of power routed to the packages with each current about 13A. The present cable resistance running from CTR to UT is 1.4Ω. So the current drawn by the packages will lead to a voltage drop of 18.2V (13A x 1.4 Ω). This drop will not meet the input specification of the DC-DC converter (26-32V). Hence chains are divided into 3 groups each, with each group having 4 lines (2 live + 2 return). The tradeoff here is that, the number of umbilical lines increases drastically. When multiple modules are being powered from a single external supply, RPV variation is seen with multiple modules ON. This is because as more modules are put ON, current drawn will be higher and so will be the voltage drop. In such a case by using constant voltage setting, it may not be possible to meet the requirement of 26-32V. In such cases, a programmable supply is a preferred solution.

VI. Conclusion

This paper discusses the power system configuration of RLV-TD. Unified redundant power bus implementation and use of Li-ion batteries makes RLV power scheme distinct from operational launch vehicles. Lithium ion batteries are used for powering avionic systems, pyro system and actuation system. Battery capacity/margin computation has been done for continuous current requirements of Avionic & BLDC Battery. Pulse current Voltage/current estimation method has been described for pyro Functions.

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